

Results of magnetic field measurements in young stars DO Tau, DR Tau, DS Tau

A. V. Dodin¹, S. A. Lamzin¹, G. A. Chountonov²

1) *Sternberg Astronomical Institute of Moscow State University, , Moscow, 119992, Russia**

2) *Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 369167, Russia*

Abstract

Results of measurements of the longitudinal magnetic field in a hot accretion spot in three classical T Tauri stars (CTTS) are presented. The magnetic field in the formation region of the narrow component of the emission line He I 5876 Å was found for each star in our sample at a level of more than 2σ . In case of DS Tau we have found the field in the narrow components of Na I D lines, which was equal to $+0.8 \pm 0.3$ kG, i.e. it was equal to the field measured on the narrow component of He I 5876 Å. Our results indicate that the magnetic field in the hot spots can be studied for CTTS down to 13^m that allow in the future to double a number of CTTS with measured field in the accretion zone.

Introduction

Classical T Tauri stars (CTTS) are young ($t < 10^7$ yr), low mass ($M \leq 3 M_\odot$) stars at the stage of gravitational contraction towards the main-sequence, activity of which is caused by magnetospheric accretion of protoplanetary disc matter [1]. Inner regions of the accretion disc are truncated by the stellar magnetic field and disc's matter slides down toward the star along the field lines. Having reached the dense layers of the stellar atmosphere, matter is decelerated in the accretion shock, behind the front of which the most part of its kinetic energy converts into the short-wavelength radiation. One half of the radiation flux irradiates the star, producing the so-called hot spot on its surface. Simulations, performed by Dodin & Lamzin [2], confirm the hypothesis, suggested by Batalha et al. [3], that the so-called narrow ($FWHM \sim 30 \text{ km s}^{-1}$) components of emission lines in spectra of CTTS are formed in this region. Hence, if the narrow components of the emission lines are used for the magnetic field measurements, then the obtained field strength characterizes the field in the accretion zone on the stellar surface.

The second half of the short-wavelength radiation flux of the shock from the cooling zone escapes upward, heating and ionizing the pre-shock gas. Broad ($FWHM > 100$

*Send offprint requests to: A. Dodin e-mail: dodin_nv@mail.ru

km s^{-1}) components of the emission lines are formed in this region as well as in a more extended region at the truncation radius, where the disc interacts with the field, and a magnetospheric wind are launched. The relation between the intensity of the narrow and broad components varies from line to line, changes over time, and for the same lines varies from star to star. Because the broad components are formed in the region at a significant distance from the stellar surface, the field strength, measured on these components, is, as a rule, in several times smaller than that, measured on the narrow ones (see, however, [4]).

The magnetic field of young stars determines an activity of CTTS and plays a crucial role in an evolution of angular momentum of these objects, therefore a question about strength and topology of the magnetic field is one of the fundamental questions of physics of young stars. At the moment, the magnetic field has been found in about 40 CTTS. These measurements are significantly differ in the methods, and therefore, the field strength, measured in different works, can relate to different spatial regions. Maps of the magnetic field at the photospheric level have been reconstructed by analysis of polarized light for the following stars: CV Cha and CR Cha [5], TW Hya [6], V2129 Oph [7], V2247 Oph [8], AA Tau [9], BP Tau [10]. The field has been detected by means of Zeeman broadening in unpolarized light in 26 stars [11, 12]. The field on the narrow emission components, which are formed in the accretion zone, has been measured only in 10 stars: RW Aur [4], TW Hya [6], V2129 Oph [7], AA Tau [9], BP Tau [10, 13, 14], GM Aur, DF Tau, DN Tau, GG Tau [13], T Tau [15].

To measure a magnetic field, spectra with a high quality are needed, therefore the observations carry out on large telescopes for bright stars with numerous strong lines. However, the number of such stars is small, and practically, it is limited by the list, presented above. If we do not aim to determine the magnetic field in the photosphere of the star, and want to determine the field only in the accretion spot at the stellar surface, by measuring the narrow components of the emission lines, then the success of the measurement is determined by the flux and shape of the profile of the lines, rather than by the brightness of the star.

Having considered a few dozen spectra of CTTS, obtained at the VLT and Keck observatories, we chose 8 relatively faint stars with the strong and narrow emission line of He I 5876, the magnetic field of which had never been measured before. In our paper the measurements for three of these eight stars are presented: DO Tau (spectral type M0, range of variability in $V = 13^m.0 - 14^m.3$ [16]), DR Tau (K5, $V = 10^m.8 - 12^m.8$ [17]), DS Tau (K5, $V = 11^m.6 - 12^m.7$ [17]).

Observations and their reduction

The method we use to measure magnetic field is based on the fact that so-called σ -components resulted in Zeeman splitting are polarized circularly such as oppositely polarized components are located on different sides of the central wavelength λ_0 . If magnetic field in a line formation region has a longitudinal component B_z then the right- and left-hand

polarized components will be shifted relative to each other to [18]:

$$\Delta_B \simeq 2.3 \cdot 10^{-2} g \left(\frac{\lambda_0}{5000} \right)^2 B_z, \quad (1)$$

where g is the Lande g -factor of the considered line, Δ_B and λ_0 are in Å and B_z is in kG. This relation allows to find the longitudinal magnetic field component B_z , averaged over the line formation region, by measuring Δ_B from two spectra observed in the right- and left-hand polarized light.

Observations were carried out on 2012 October 26-27 with the Main Stellar Spectrograph¹ [19] of 6-m telescope of Special Astrophysical Observatory equipped with a polarization $\lambda/4$ -plate and a double slicer [20]. The spectrograph slit width was 0."5. The observations were carried out in the spectral range 5640-6480 Å by using CCD array (E2V CCD42-90), the size of which along the dispersion was 4600 pixels that corresponds to the inverse linear dispersion of 0.183 Å/pixel.

Spectra were processed as follows [14]. Night sky emission and detector bias as well as cosmic ray traces were removed in a standard way, using routines from the MIDAS software package. A spectrum of a thorium-argon lamp was used for a wavelength calibration. Each observed spectrum was transformed into the stellar rest frame by shifting it as a whole (by radial velocity) until a coincidence of photospheric lines in the observed and simulated spectra [2]. The log of the observations is presented in Table 1, which contains Julian Date JD of the middle of an observation, an exposure time and a signal-to-noise ratio S/N.

To exclude systematic instrumental errors, our observations were organized as follows. One measurement of the field needed two exposures, between which the superachromatic quarter-wave phase plate was rotated in such a way that the right- and left-hand polarized spectra changed places on the CCD array. Thus, we get four spectra of the star: right- and left-hand polarized at the first exposure R_1 , L_1 and similar spectra of R_2 , L_2 at the second exposure.

Further we calculated the difference between the positions of the lines in the spectra R_1 and L_1 , which we denoted as Δ_1 , between R_2 and L_2 , which we denoted as Δ_2 and between R_1+L_1 and R_2+L_2 , which we denoted as Δ_3 . Here $R+L$ denotes the sum of simultaneously obtained spectra. These differences were calculated by using the crosscorrelation method [21] for the confidence level $\alpha = 0.68$, that corresponds to 1σ error. The shift due to Zeeman effect is equal to

$$\Delta_B = \frac{\Delta_1 + \Delta_2}{2},$$

a mean systematic shift between R and L :

$$\Delta = \frac{\Delta_2 - \Delta_1}{2},$$

and a systematic shift between two exposures:

$$\delta = \Delta_3.$$

¹The description is available at: <http://www.sao.ru/hq/lizm/mss/ru/tech.html> (in russian)

Таблица 1: Log of observations.

N	JD 245 6220+	Star	t_{exp} , sec	S/N
1	7.181	γ Equ	180	360
2	7.186	γ Equ	180	360
3	7.299	HD216228	100	180
4	7.324	DS Tau	1200	62
5	7.354	DS Tau	1200	64
6	7.383	DS Tau	1200	60
7	7.420	DR Tau	1200	123
8	7.449	DR Tau	1200	119
9	7.479	DR Tau	1200	113
10	7.510	DO Tau	1200	83
11	7.540	DO Tau	1200	78
12	7.628	HD31398	100	110
13	7.638	53 Cam	300	370
14	8.212	γ Equ	180	310
15	8.336	DS Tau	1200	72
16	8.365	DS Tau	1200	70
17	8.394	DS Tau	1200	78
18	8.429	DO Tau	1200	49
19	8.458	DO Tau	1200	49
20	8.488	DO Tau	1200	44
21	8.521	DR Tau	1200	88
22	8.550	DR Tau	1200	89
23	8.579	DR Tau	1200	84
24	8.639	53 Cam	300	350

N is a sequence number of an observation, which consists of two expositions, t_{exp} is an exposure time of these expositions. S/N is a signal-to-noise ratio at a continuum level for each exposition.

All shifts were calculated in pixels, and then, if necessary, were translated in Å. We used this method to measure B_z on the lines He I 5876, Na I D and [O I] 6300.

However, in the case of the field measurements on many lines, it is appropriate to measure the shifts all considered lines at once. In this case, the procedure of measurements Δ_B should be refined. The shifts Δ_i ($i = 1, 2$), calculated by the crosscorrelation method, include two shifts of different nature: Δ_B and Δ . On the one hand, the shift Δ_B is different for each spectral line, therefore to find Δ_i by calculating the maximum of the correlation function, we should choose the value of B_z as an independent variable, because it is the same for all lines, while the shift of each line should be calculated by the formula (1). On the other hand, the systematic shift Δ is assumed to be constant for the entire spectrum, therefore to find it, we should choose a shift of the spectrum as a whole as the independent variable.

To combine these contradictory requirements, we had found an average systematic shift $\overline{\Delta}$, assuming that it behaves like Δ_B and then we corrected the spectrum for this shift $\overline{\Delta}$. Because $\Delta \neq \overline{\Delta}$, this correction does not eliminate the systematic error, but only reduces it. However, 3-4 iterations of the procedure allow to eliminate the systematic shift almost entirely. An uncertainty of the value Δ_B , defined in this manner, equals to $0.5 \sqrt{\sigma_{\Delta 1}^2 + \sigma_{\Delta 2}^2}$.

Lande factors of photospheric lines were adopted from the VALD database [22]. In the case of blended photospheric lines g -factors were averaged with weights of a central depth:

$$g_{ef}(\lambda) = \frac{\sum g_i f_i(\lambda)}{\sum f_i(\lambda)},$$

where $f_i(\lambda)$ is a gaussian profile of an i -th line in the blend. The width of the gaussian was found from the observed spectrum, and the amplitude was equated to the line depth from the VALD database. We take into account all photospheric lines with known Lande factors g_i , which fall in our spectral range and have a central depth greater than 0.1. Lande factors for emission lines, considered in our paper: He I 5876 (excitation potential $\epsilon = 23.07$ eV), [O I] 6300 ($\epsilon = 1.97$ eV) and Na I 5890, 5896 ($\epsilon = 2.10$ eV) were assumed to be 1.1, 1.0, 1.33, correspondingly.

To test the described method, we have observed stars with a known magnetic field: 53 Cam and γ Equ, as well as giants: HD 216228 and HD 31398, the field of which should be close to zero. The results of the measurements B_z are presented in the Table 2. It can be seen from the table that the values of B_z are equal to zero within its uncertainties in case of HD 216228 and HD 31398 and, in case of γ Equ, B_z agree with the results, obtained by Kudryavtsev & Romanyuk [23], who have found that for this star B_z varies from -0.85 to -1.25 kG. These results convince us of the correctness of the chosen method. In case of 53 Cam, the result of second measurement coincides within the error with the expected value, calculated from the formulas from Hill's paper [24], but B_z of first measurement differs noticeably from the predicted value. Note that similar and even greater deviations from the predicted values were also observed in 53 Cam by other authors [23].

Таблица 2: Test measurements of the field

N	JD 245 6220+	Star	B_z	σ_B	B_e
1	7.181	γ Equ	-1.00	0.09	-1.1 ^a
2	7.186	γ Equ	-0.94	0.09	-1.1 ^a
3	7.299	HD 216228	-0.05	0.04	0.0
12	7.628	HD 31398	-0.03	0.04	0.0
13	7.638	53 Cam	-2.50	0.09	-1.4 ^b
14	8.212	γ Equ	-0.89	0.09	-1.1 ^a
24	8.639	53 Cam	+1.92	0.11	+2.1 ^b

B_z and σ_B are the value of the measured field and its uncertainty, in kG. B_e – an expected value of the field in kG: (a) marks a mean value from the paper by Kudryavtsev & Romanyuk [23], (b) marks a predicted value from the paper by Hill et al. [24].

Results

CTTS usually have a period of axial rotation about a week [25], therefore it can be expected that the field could not change significantly during the time of the observation of every star within each night (around 2 hours). Hence, there are reasons to calculate an average B_z for each night:

$$\overline{B_z} = \frac{\sum(B_{zi}/\sigma_i^2)}{\sum(1/\sigma_i^2)}.$$

An error σ_i of an individual observation was estimated from the uncertainties of Δ_1 , Δ_2 , as it was described in the previous section.

A scatter of the individual observations B_{zi} during one night may be caused by the noise of the spectrum. In this case an uncertainty of the average can be estimated as:

$$\sigma_a = \left[\sum(1/\sigma_i^2) \right]^{-1/2}.$$

However, we can not exclude that the scatter may be caused by some other random process, for which the standard deviation can be estimated as follows:

$$\sigma_b = t(n-1, 1-0.5 \cdot [1-P]) \times \sqrt{\frac{1}{(n-1) \sum(1/\sigma_i^2)} \sum \frac{(B_{zi} - \overline{B_z})^2}{\sigma_i^2}},$$

where $P = 0.68$ is the confidence level corresponding to 1σ , n is the number of measurements being averaged, t – the inverse of Student's T cumulative distribution function. If there are both processes, and they are independent, then a total error of the average over night can be estimated as $\sigma_{\overline{B}} = \sqrt{\sigma_a^2 + \sigma_b^2}$. The values of $\overline{B_z}$ and $\sigma_{\overline{B}}$ are given in the Table. 3.

It follows from the Table 3 that the fields have been detected in the formation region of the narrow component of the line He I 5876 in the stars DO Tau and DS Tau at a level $> 2\sigma$ and in the star DR Tau at a level $> 3\sigma$. Examples of I -profiles for the given line for these stars are presented on the Fig. 1. Vertical dashed lines mark the part of the profile

Таблица 3: The results of the field measurements in CTTS

Star	N-N	$\overline{B_z}$ He I 5876	$\sigma_{\overline{B}}$	$\overline{B_z}$ Na I D	$\sigma_{\overline{B}}$	$\overline{B_z}$ 6300 [O I]	$\sigma_{\overline{B}}$	$\overline{B_z}$ The photosphere	$\sigma_{\overline{B}}$
DO Tau	10–11	−0.79	0.27	−0.13	0.30	−0.01	0.31	+0.23	0.29
	18–20	−0.45	0.36	+0.20	0.51	+0.08	0.40	−0.14	0.44
DR Tau	7–9	−0.94	0.32	−0.29	0.46	−0.16	0.36	−0.11	0.45
	21–23	−1.51	0.37	−0.44	0.30	−0.03	0.31	−0.55	0.41
DS Tau	4–6	+0.32	1.97	—	—	−0.28	0.63	+0.05	0.70
	15–17	+0.80	0.34	—	—	+0.56	0.70	+0.02	0.64

N–N is the sequence numbers from the Table 1, $\overline{B_z}$ and $\sigma_{\overline{B}}$ are the value of longitudinal component of the field and its uncertainty, in kG.

(21 pixels), which was used in the measurement. A variation of the equivalent width of the line from night to night can be caused either by the stellar rotation or by changes of physical conditions in the accretion spot. It manifested most clearly in the case of DS Tau: the line of He I 5876 in first night was approximately six times smaller than in second night.

Dots on the figure correspond to an "observed" V -profile, which was calculated by using the left- and right-polarized spectra, summarized pixel by pixel over the two exposures and corrected for Δ and δ :

$$R = R_1(\lambda) + R_2(\lambda - \Delta - \delta),$$

$$L = L_1(\lambda - \Delta) + L_2(\lambda - \delta),$$

$$V = 2 \frac{R - L}{R + L}.$$

The shifts Δ and δ are about tenths of a pixel, therefore to calculate the values of R_2 and L_2 for fractional pixel values, we use a linear interpolation, which leads to a slight smoothing of the spectra. A thin line on the figure shows a "theoretical" V -profile, which was calculated as a relative difference of two I -profiles, the first of which was shifted by $\Delta_B/2$ to the left and the second was shifted by the same amount to the right.

In case of DO Tau and DR Tau the broad emission component (see Fig. 2) dominated in Na I D lines, the field on which was measured on both line simultaneously on the spectral range 5885.6 – 5900.3 Å. Results of the measurements are collected in the the Table 3 and they show that the value $\overline{B_z}$ in the broad emission components of Na I D is equal to zero with accuracy better than $\sim 1.5\sigma$ that is typical for the broad components of emission lines in CTTS (see the Introduction).

The broad emission component of Na I D lines is absent in DS Tau and the lines consist from broad photospheric absorption wings and the narrow emission component. The value of B_z , measured on the narrow components and averaged over first night (numbers 4-6 from the Table. 1), was equal to -0.21 ± 0.34 kG. In other words, the field in a line formation region of Na I D as well as He I 5876 has not been detected in this night.

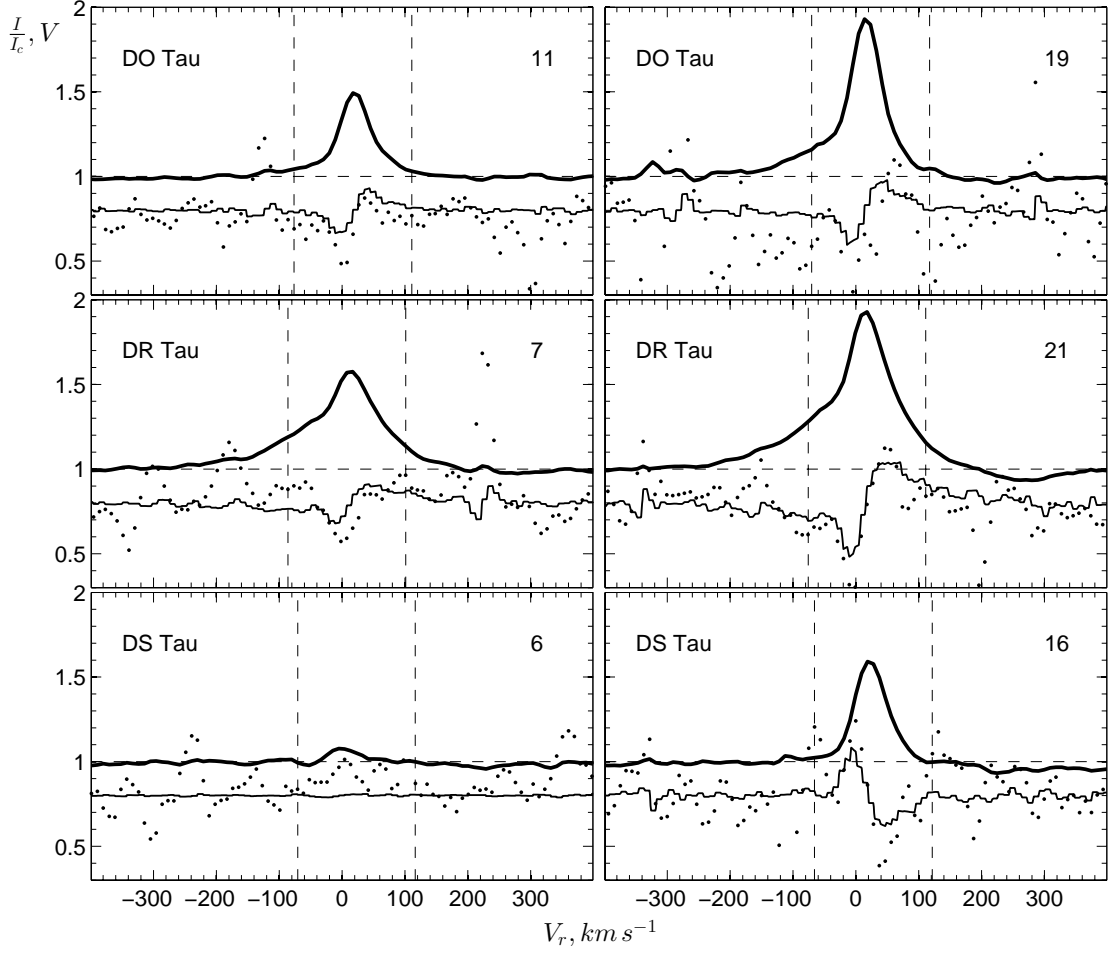


Рис. 1: Examples of I – and V –profiles near the line HeI 5876 for the stars DO Tau, DR Tau, DS Tau. The left and right panels correspond to the observation on October 26 and 27, correspondingly. The number in the upper right corner of each panel corresponds to the number in the Table 1. The thick curve indicates the observed I –profile. The dots indicate the observed V –profile. The thin curve indicates the predicted V –profile for the field value from the Table 3. Both V –profiles were multiplied by 10 times and shifted to 0.8 for readability. Dashed lines mark the continuum level and a spectral range, on which we measure the field. An abscissa is the velocity in km s^{-1} from the line center $\lambda_0 = 5875.6 \text{ \AA}$ in the stellar reference frame.

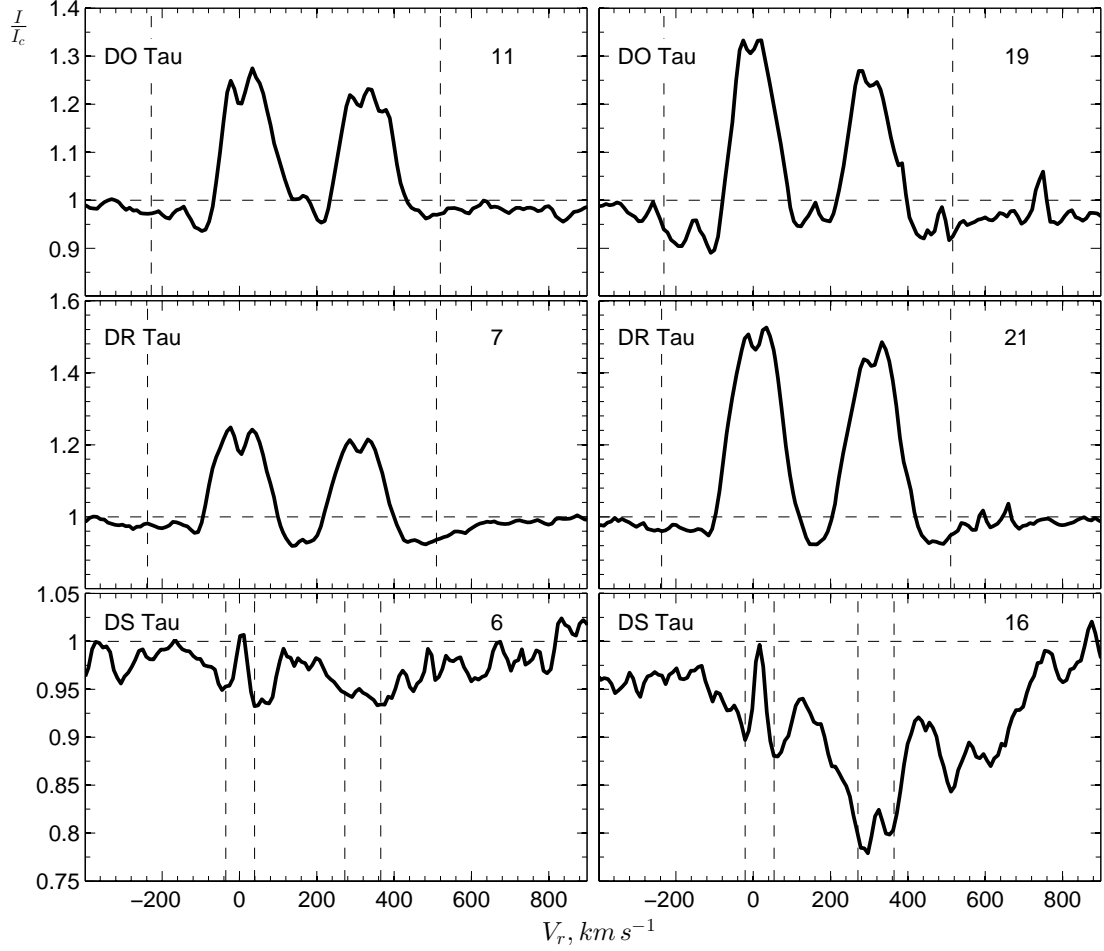


Рис. 2: Examples of I -profiles near the line Na I D for the stars DO Tau, DR Tau, DS Tau at the first night (the left column) and at the second night (the right corner). The number in the upper right corner of each panel corresponds to the number in the Table 1. Dashed lines mark the continuum level and a spectral range, on which we measure the field. An abscissa is the velocity in km s^{-1} from the line center $\lambda_0 = 5889.95 \text{ \AA}$ in the stellar reference frame.

However, similar measurements in the next night (the observations 15-17) gave the values $\overline{B_z} = +0.79 \pm 0.34$, which well coincided with $\overline{B_z}$, measured on He I 5876: $+0.80 \pm 0.34$ kG.

The field measured on the forbidden line of [O I] 6300 is always inside its uncertainty, because the line are formed at low gas densities in a large volume, where the magnetic field is close to zero. The measurements of this line were carried out to check the absence of large systematic errors in the method of processing the spectrum.

The field, measured on photospheric lines, in all considered stars is equal to zero within its uncertainty. This seems to be due to two effects. First, we observed faint CTTS, and the signal-to-noise ratio for them was usually much lower than, for example, in case of the test stars, moreover, the radiation of the accretion spot leads to a significant shallowing the absorption lines in CTTS spectra (so-called veiling), that increases the error of $\overline{B_z}$. Second, we measure only the longitudinal component of the field. Hence, even if the field in the photosphere is the same as in the line formation region of He I 5876, then the longitudinal component of the field, averaged over the entire visible surface of the star, is several times lower than in the line He I 5876, for which the field is averaged only over the accretion spot. [26].

Conclusion

The possibility of determining the magnetic field in the accretion spot in a relatively faint CTTS by measuring the Zeeman splitting of the narrow component of strong emission lines in their spectra has been demonstrated on examples of three stars. Following the tradition, we have measured the field on the line He I 5876, but lines of other elements, which as well as He I 5876 are formed in the accretion spot, can be also used in the future.

The measured values of B_z are the values of the longitudinal component of the field, which is averaged over the accretion spot with weights of the line intensity in each point of the spot. Dodin et al. [27] have shown that there are lines in spectra of CTTS, the intensities of which vary in different ways depending on the accretion flux $F_{ac} = \rho_0 V_0^3 / 2$, where ρ_0 and V_0 are a pre-shock gas density and velocity, correspondingly. For instance, the intensity of Ca I lines is increased with increasing of F_{ac} , and vice versa Ca II lines get smaller. It gives a possibility to use such lines for the measurements of the magnetic field in parts of the accretion spot with different values of the accretion flux F_{ac} .

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